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Liner Materials Exposed to Toxic and Hazardous Wastes

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16. ABSTRACT

This exploratory experimental research project was conducted (1975-1983) to assess the relative effectiveness and durability of a wide variety of liner materials when exposed to hazardous wastes under conditions that simulate different aspects of service in on-land waste storage and disposal facilities. The materials studied included compacted soil, polymer-treated bentonite-sand mixtures, soil cement, hydraulic asphalt concrete, sprayed-on asphalt, and 31 flexible polymeric membranes based on polyvinyl chloride, chlorinated polyethylene, chlorosulfonated polyethylene, ethylene propylene rubber, neoprene, butyl rubber, elasticized polyolefin, and polyester elastomer. Four semicrystalline polymeric sheetings (polybutylene, low-density polyethylene, high-density polyethylene, and polypropylene), though not compounded for use as liners, were included in the study because of their known chemical-resistance and use in applications requiring good chemical and aging resistance.

The lining materials were exposed in test cells to 10 actual waste liquids, including two acidic wastes, two alkaline wastes, three oily wastes, a blend of lead wastes, a pesticide waste, and an industrial waste. The polymeric materials were also exposed to three media of known composition, deionized water, 5% aqueous solution of salt, and a saturated solution of low concentration (0.1%) of an organic, tributyl phosphate. The experimental approach and methodology followed are described. The polymeric materials were also exposed to wastes or environmental conditions under a variety of procedures which included primary one-side exposure, immersion-type testing, two types of outdoor exposure, and a pouch test. Some of the exposures were for as long as 2700 days. New methods for the testing of polymeric materials are presented.

The response of the lining material to the waste liquids and test media ranged from little or no effect to severe effects and failure. Oily wastes appeared to have the greatest effect on polymeric membranes. Some organics, even at low concentrations, can have severe effects in long exposures as was shown by the lead waste and the dilute but saturated solution of tributyl phosphate.

Because of the wide differences in the interaction of lining materials and wastes due to their uncertainty and complexity of composition, compatibility testing of the candidate liner and the specific waste or prototype of the waste to be impounded should be part of the process for selecting lining materials for that application.

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LINER MATERIALS EXPOSED TO TOXIC AND HAZARDOUS WASTES

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A research project was undertaken to assess the relative effectiveness and durability of a wide variety of liner materials when exposed to hazardous wastes under conditions simulating various aspects of service in waste storage and disposal facilities. The materials studied included compacted soil, admixes, sprayed-on asphalt and 32 polymeric membranes. Four partially crystalline polymeric sheetings, though not compounded for use as liners, were included in the study because of their known chemical resistance and their use in applications requiring good chemical and ageing resistance.

The lining materials were exposed in test cells to 10 hazardous wastes (two acidic, two alkaline, three oil, a blend of lead, a pesticide and a briny industrial waste) and three media of known composition—deionized water, 5% aqueous solution of salt and a saturated solution of low-concentration (0.1%) tributyl phosphate. The polymeric materials were also exposed to wastes or environmental conditions under a variety of conditions that included primary one-sided exposure, immersion testing, two types of outdoor exposure and a pouch test. Some of the exposures were as long as 2700 days. New methods for testing polymeric materials are presented. Results indicated that some of the liner materials performed satisfactorily in contact with certain wastes but, because waste combinations can be highly specific, compatibility testing is needed to select a liner for a given waste.

Key Words—Liners, hazardous and toxic wastes, compacted soil, admixes, sprayed-on asphalt, polymeric membranes, exposure testing, immersion testing, test cells, pouches.

1. Introduction

Land disposal studies in the early 1970s clearly indicated the need for positive control measures to prevent contamination of the surface water and groundwater that might result from storage and disposal of hazardous wastes on land. The use of man-made liner materials of low permeability appeared to be a feasible means of preventing the pollutants in hazardous wastes from entering the groundwater. Some lining materials have been used for 20 years or more to impound water. Liners have also been used to impound brines and some wastes. A wide range of materials differing in permeability, composition, construction and cost have been used or are potentially useful for confining possible pollutants. Nevertheless, few data are available on the relative performance and service lives of specific materials exposed to certain wastes. The U.S. Environmental Protection Agency (EPA) needed considerably more information to guide and perhaps eventually to regulate the use of liners in these applications. Furthermore, information was needed by designers and facility owners to help them select materials for lining disposal facilities.

An exploratory approach was taken to meet these broad information needs. The first step of the project was to extend the information that had been accumulated in

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an earlier project on liners for containing municipal solid waste (Haxo *et al.* 1982, 1985). Liner technology had progressed considerably in the 2 years since that project had begun, and the present project needed to take advantage of the more current technology. In-depth information was also needed on some of the most used liner materials, so this project included some of the membranes studied in the earlier study on municipal waste liners.

This project was started in 1975 with the following broad objectives.

1. To determine how a selected group of lining materials is affected by exposure to a range of hazardous wastes over a relatively extended period (2 years).
2. To determine the durability and cost effectiveness of polymeric membranes, sprayed-on membranes, admixed materials and natural soils as liners for hazardous waste storage and disposal facilities.
3. To estimate the effective lives of 12 liner materials exposed to six types of nonradioactive hazardous waste streams under conditions that simulate those encountered in waste impoundment and disposal facilities.
4. To develop information needed for selecting specific lining materials to confine hazardous wastes in specific installations.
5. To develop methods for assessing the relative merits of the various lining materials for specific applications and for determining their service lives.
6. To develop indicator tests that could be used to select lining materials for given applications.
7. To help the EPA develop effective controls for the proper disposal and management of hazardous wastes.

Results of this project have been reported over the past several years in various preliminary documents. The final report (Haxo *et al.* 1984) presents the results of the complete project and includes information on the exposure of lining materials for periods of up to 2700 days, over 7 years, (most of the exposure data are for periods of up to 1350 days, however).

2. Materials and methods

2.1. *Types of liners used*

This research program determined the effects of exposing a broad range of selected liner materials to a range of wastes, sludges and test media under a variety of test conditions for periods of up to 2700 days. The four types of liner materials included in the program were:

1. one compacted soil of low permeability;
2. three admixes (asphalt concrete, polymer-treated bentonite and sand mixtures and a hydraulic cement);
3. one sprayed-on membrane of an emulsified asphalt on a nonwoven fabric; and
4. thirty-two different commercial polymeric sheetings based on the following polymer types: butyl rubber, chlorinated polyethylene (CPE), chlorosulfonated polyethylene (CSPE), elasticized polyolefin, neoprene, polybutylene, polyester elastomer, low- and high-density polyethylene (LDPE and HPDE), polypropylene and polyvinyl chloride (PVC).

The polymeric materials covered a range of thicknesses, manufacturers, and cross-linked and thermoplastic variations of the same polymers. Some were fabric-reinforced sheetings. Most of the sheetings selected for study were commercial membranes used for lining pits, ponds, and lagoons. Others were prototype materials or sheetings of polymers that were promising as liners. Many of the lining materials had previously been tested by exposure to municipal landfill leachate (Haxo *et al.* 1982, 1985). When the project was initiated, lining materials based on HDPE had not been commercially introduced in the United States.

Single samples of sheeting of polybutylene, low- and high-density polyethylene, and polypropylene were included in the study because of their promising characteristics and their use in pipes and containers for handling corrosive chemicals. None of the sheetings contained carbon black to reduce photodegradation, and none were designed specifically as linings for waste disposal facilities.

2.2. *Wastes used in the tests*

The wastes used in the tests represented several general types of actual waste liquids including two acidic wastes (one with pH < 1.0), two alkaline wastes 'one with pH of > 12.5), one briny industrial waste (with high concentrations of trace metals and organics), one lead waste contining oil, three oil wastes and one pesticide waste. In addition, three test fluids of known composition were included as reference points: deionized water, a 5% solution of salt and water, and a saturated solution of tributyl phosphate (0.1%). The first two fluids could be used as standard references, as many of the wastes that are encountered contain water and salt. The saturated solution of tributyl phosphate was included to assess the effect that occurs when polymeric membranes absorb an organic chemical from an aqueous solution of known low concentration.

2.3. *Test methods*

Four major types of exposure tests were conducted on the lining materials: a one-sided exposure to the wastes, a two-sided exposure to the wastes by immersion, an outdoor exposure, and a pouch test.

2.3.1. *One-sided exposure to the wastes*

In this primary test of the project, liner specimens about 0.092 m^2 (1 ft^2) were mounted in cells (Fig. 1), and a 0.30-m (1-ft) head of waste was placed on them. This test was designed to simulate a liner at the bottom of a pond. The permeability of the material could be assessed by collecting seepage below the liner specimen. Durability was measured in terms of physical property retention after two exposure periods. Included in this exposure test were all four types of lining materials—compacted soils, admixed, sprayed-on asphaltic membranes and polymeric sheetings. Tables 1–4 summarize the results of testing the polymeric sheetings after exposure. The durations of exposure for the data presented in these tables are presented in Table 5.

2.3.2. *Two-sided exposure to the wastes by immersion*

Samples of 16 polymeric membrane liners were suspended in the tanks of the above cells containing 13 waste liquids and test media. In most cases, two specimens of a membrane were placed in the liquid, withdrawn at two different times and subjected to a series of tests, including measurement of dimensions, weight increase, volatiles content, extractables content, and such physical tests as tensile, tear and puncture resistance.

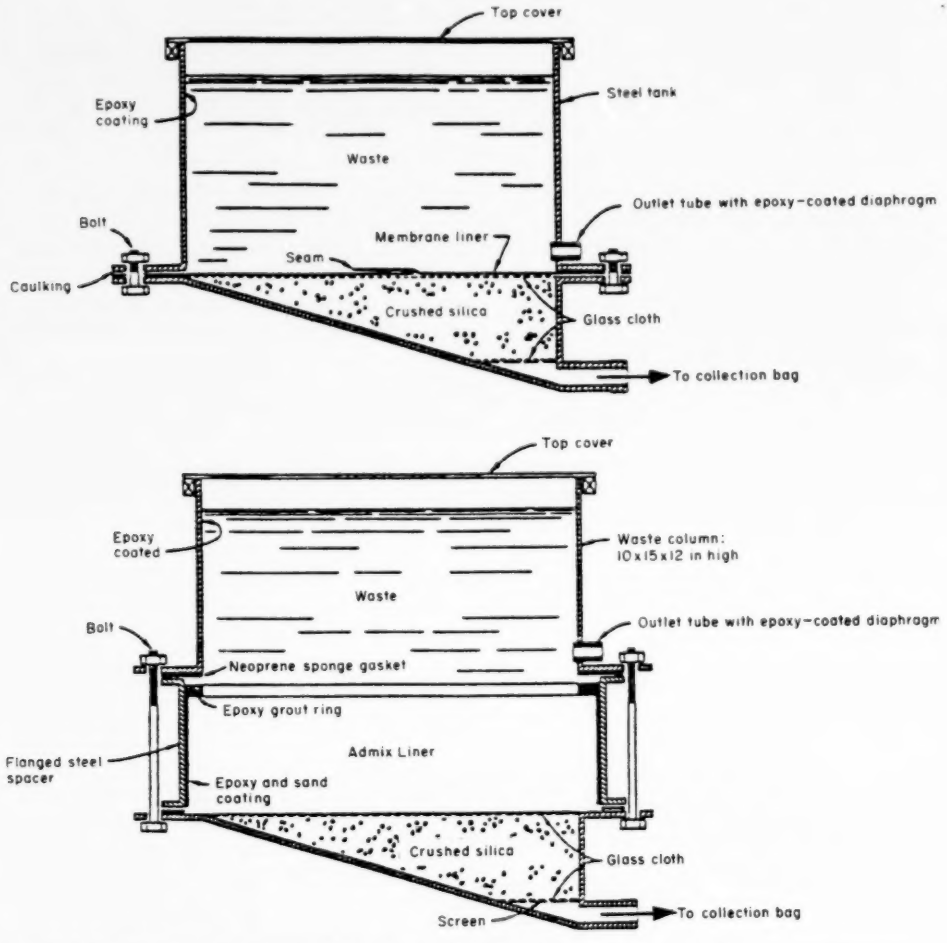

Fig. 1. Design of cells for long-term exposure of membrane liners (top) and soil and admix liners (bottom) to various hazardous wastes.

2.3.3. *Outdoor exposure*

Two types of outdoor exposures were conducted. The first exposed polymeric membrane samples to weathering, and the second exposed samples intermittently to both weathering and a waste. For the weathering-only exposure, three specimens for each of the polymeric membranes were placed on a roof rack in Oakland, California. One specimen was removed after each of three time periods. The specimens were measured for dimensional changes and then tested by methods similar to those in the immersion test. For the weathering and waste exposures, polymeric membrane specimens were used to line small tubs that were partially filled with hazardous wastes. The tubs were covered with chicken wire and placed in a shallow basin lined with an elasticized polyolefin membrane. During rainy weather, these cells were protected by a corrugated plastic cover. This test allowed assessment of weather and waste exposure on the liner

TABLE 1

Exposure of polymeric membrane liner specimens in primary cells*—% volatiles

Polymeric membrane liner		Original value (%)	Wastes								
			Acidic		Alkaline			Oily			Pesticide
Polymer	Number†		HFL	HNO_3-HF-HOAc	Slop water	Spent caustic	Lead waste	Slurry oil	Oil Pond 104	Weed oil	Weed killer
Butyl rubber	57R	0.29	—	5.92	—	1.75	2.79	—	—	—	4.10
			—	11.46	—	1.37	3.53	—	—	—	4.79
Chlorinated polyethylene	77	0.14	—	7.82	—	2.32	11.58	—	3.69	—	4.99
			—	13.18	—	2.79	19.20	—	10.11	—	7.91
Chlorosulfonated polyethylene	6R	0.51	—	4.69	—	4.77	1.08	—	7.51	—	8.00
			—	7.18	—	5.77	11.44	—	10.25	—	9.73
Elasticized polyolefin	36	0.15	1.46	3.20	10.83	1.25	1.03	0.38	2.15	—	0.13
			—	5.26	—	1.01	1.53	4.02	5.12	—	0.58
Ethylene propylene rubber	26	0.50	—	8.95	—	1.27	2.83	—	—	—	3.34
			—	12.02	—	1.31	5.25	—	—	—	6.29
Neoprene	43	0.45	—	—	—	4.40	18.01	—	12.99	—	11.29
			—	—	—	5.67	17.50	—	21.31	—	13.63
Polyester elastomer	75	0.26	—	0.39	—	0.65	2.63	0.40	1.27	—	0.60
			—	4.74	—	0.89	1.72	—	2.59	—	2.92
Polyvinyl chloride	59	0.31	9.90	12.08	18.72	2.34	3.34	0.29	1.70	—	2.30
			—	13.94	—	1.85	4.43	—	4.19	—	3.16

* Respective durations of exposure are presented in Table 5.

† Matrecon liner serial number; R = fabric reinforced.

TABLE 2
Exposure of polymeric membrane liner specimens in primary cells*—% extractables

Polymeric membrane liner		Original value (%)	Wastes								
			Acidic		Alkaline			Oily			Pesticide
Polymer	Number†		HFL	HNO_3-HF-HOAc	Slop water	Spent caustic	Lead waste	Slurry oil	Oil Pond 104	Weed oil	Weed killer
Butyl rubber	57R	6.36	—	—	—	—	7.75	—	—	—	5.15
			—	8.65	—	7.86	7.86	—	—	—	7.62
Chlorinated polyethylene	77	9.13	—	10.09	—	—	7.31	—	—	—	9.72
			—	9.41	—	9.10	7.24	—	17.00	—	9.41
Chlorosulfonated polyethylene	6R	3.77	—	—	—	4.77	3.52	—	—	—	4.13
			—	4.62	—	5.77	5.95	—	9.45	—	5.39
Elasticized polyolefin	36	5.50	5.40	5.40	1.70	—	5.66	13.94	13.72	—	7.14
			—	7.09	—	5.96	8.06	23.88	20.74	—	6.86
Ethylene propylene rubber	26	22.96	—	21.36	—	—	22.27	—	—	—	23.13
			—	—	—	23.95	26.01	—	—	—	25.20
Neoprene	43	13.69	—	—	—	—	12.54	—	—	—	13.25
			—	—	—	13.69	12.15	—	15.86	—	16.14
Polyester elastomer	75	2.74	—	10.77	—	3.85	2.98	9.91	5.68	—	5.15
			—	13.36	—	3.31	5.35	—	7.28	—	5.83
Polyvinyl chloride	59	35.86	34.42	16.68	10.40	34.62	33.47	39.63	32.62	—	35.27
			—	18.58	—	35.61	22.47	—	29.99	—	33.39

* Respective durations of exposure are presented in Table 5.
† Matrecon liner serial number; R = fabric reinforced.

TABLE 3

Exposure of polymeric membrane liner specimens in primary cells*—% retention of elongation at break

Polymeric membrane liner		Original value (%)	Wastes								
			Acidic		Alkaline			Oily			Pesticide
Polymer	Number†		HFL	HNO_3-HF-HOAc	Slop water	Spent caustic	Lead waste	Slurry oil	Oil Pond 104	Weed oil	Weed killer
Butyl rubber	57R	42‡	—	60	—	60	119	—	—	—	143
			—	645	—	219	167	—	—	—	100
Chlorinated polyethylene	77	402	—	89	—	107	101	—	98	—	100
			—	89	—	88	83	—	88	—	89
Chlorosulfonated polyethylene	6R	242	—	90	—	70	107	—	103	—	112
			—	79	—	65	77	—	72	—	85
Elasticized polyolefin	36	665	98	99	88	100	92	96	86	—	101
			—	96	—	97	94	97	78	—	97
Ethylene propylene rubber	26	450	—	97	—	102	100	—	—	—	100
			—	94	—	95	106	—	—	—	104
Neoprene	43	320	—	—	—	98	76	—	86	—	93
			—	—	—	95	75	—	92	—	83
Polyester elastomer	75	575	—	<1	—	86	98	77	95	—	96
			—	4	—	86	90	—	92	—	87
Polyvinyl chloride	59	375	88	82	3	102	95	90	85	—	101
			—	71	—	97	93	—	85	—	95

* Respective durations of exposure are presented in Table 5.

† Matrecon liner serial number; R = fabric reinforced.

‡ Value reported is elongation at ultimate break with respective retention values.

Fabric in sheeting retained its original elongation (25%).

TABLE 4
Exposure of polymeric membrane liner specimens in primary cells* — % retention of stress at 100% elongaton

Polymeric membrane liner		Original value (psi)	Wastes								
			Acidic		Alkaline			Oily			Pesticide
Polymer	Number†		HFL	HNO_3-HF-HOAc	Slop water	Spent caustic	Lead waste	Slurry oil	Oil Pond 104	Weed oil	Weed killer
Butyl rubber	57R	‡	—	—	—	—	—	—	—	—	—
Chlorinated polyethylene	77	900	—	97	—	82	56	—	53	—	94
			—	113	—	129	71	—	62	—	113
Chlorosulfonated polyethylene	6R	937	—	106	—	165	85	—	63	—	90
			—	112	—	200	118	—	96	—	118
Elasticized polyolefin	36	922	98	92	97	87	95	70	61	—	104
			—	98	—	87	104	60	71	—	91
Ethylene propylene rubber	26	357	—	81	—	88	84	—	—	—	89
			—	70	—	108	80	—	—	—	87
Neoprene	43	460	—	—	—	90	53	—	50	—	62
			—	—	—	95	61	—	42	—	54
Polyester elastomer	75	2585	—	—	—	101	88	77	94	—	95
			—	—	—	109	88	—	85	—	96
Polyvinyl chloride	59	995	153	200	—	99	82	113	152	—	100
			—	249	—	115	103	—	174	—	137

* Respective durations of exposure are presented in Table 5.
† Matrecon liner serial number; R = fabric reinforced.
‡ Unexposed material broke at less than 100% elongation.

TABLE 5

Exposure of polymeric membrane liner specimens in primary cells—days of exposure

Polymeric membrane liner		Waste								
		Acidic		Alkaline			Oily			Pesticide
Polymer	Number*	HFL	HNO_3-HF-HOAc	Slop water	Spent caustic	Lead waste	Slurry oil	Oil Pond 104	Weed oil	Weed killer
Butyl rubber	57R	—	505	—	526	499	—	—	—	500
		—	1218	—	1249	1339	—	—	—	1258
Chlorinated polyethylene	77	—	459	—	526	499	—	521	—	500
		—	1218	—	1249	1334	—	1358	—	1258
Chlorosulfonated polyethylene	6R	—	505	—	526	499	—	521	—	504
		—	1218	—	1249	1343	—	1357	—	1258
Elasticized polyolefin	36	2293	505	2300	526	499	327	521	—	494
		—	1217	—	2677	1343	2355	1357	—	2699
Ethylene propylene rubber	26	—	497	—	526	499	—	—	—	500
		—	1147	—	1249	1344	—	—	—	1258
Neoprene	43	—	—	—	526	499	—	521	—	494
		—	—	—	1237	1342	—	1356	—	1257
Polyester elastomer	75	—	323	—	526	499	328	521	—	501
		—	509	—	1237	1342	—	1357	—	1258
Polyvinyl chloride	59	1565	505	1565	526	499	327	521	—	500
			1352	—	1249	1345	—	1356	—	1258

*Matrecon liner serial number: R = fabric-reinforced.

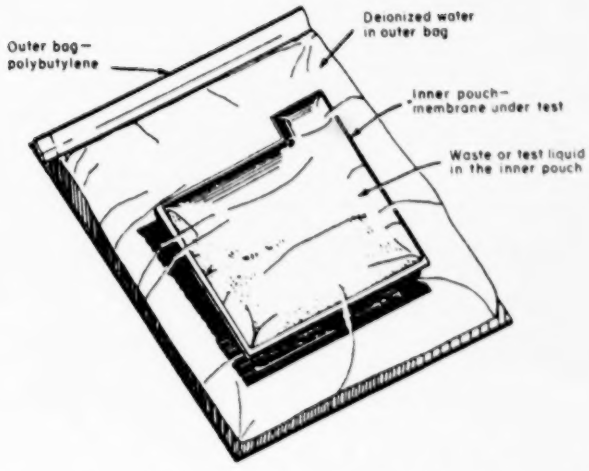

Fig. 2. Schematic of pouch assembly showing inner pouch made of membrane material under test. The pouch is filled with waste liquid and sealed at the neck. The outer polybutylene bag, which can be easily opened, is filled with deionized water.

below, above and at the interface of the waste and air, and it tested the effect of directional orientation. The liner specimens in the tubs contained a field seam so that the effects of waste on seam strength could also be assessed.

2.3.4. *Pouch test*

Pouches fabricated from polymeric membranes were filled with wastes and sealed (Fig. 2). The sealed pouches were immersed in deionized water and exposed for extended periods. The permeability of the membranes could be assessed by measuring at various time intervals the weight changes in the pouch, and the conductivity and pH changes of the deionized water in which the pouches were placed (Table 6). When the pouches were eventually dismantled, dissected and tested, they also yielded information on one-sided exposure to waste.

The duration of these tests ranged up to 2700 days for the primary one-sided exposure tests, 1456 days for the immersion test, 1231 days for the roof rack test and more than 2500 days for some of the tubs. Some of the pouch tests ran as long as 2000 days.

3. Results

The project was concerned principally with the chemical compatibility of materials as measured by the liner's absorption of the waste solution, changes in mechanical properties and (in some cases) changes in permeability. Results indicated that some of the liner materials performed satisfactorily in contact with certain wastes but, because waste combinations can be highly specific, compatibility testing is needed to select a liner for a given waste.

3.1. *Lining Materials*

3.1.1. *Soil liner*

Specimens of the native liner performed quite satisfactorily and showed only modest effects during the 6.5 years of exposure to each of five waste liquids—low-alkalinity waste (spent caustic), lead waste, oily wastes (slurry oil and Oil Pond 104) and pesticide waste. Combinations of the soil liner with the acidic wastes were eliminated in the screening tests because of apparent incompatibility.

With all wastes, the 1-ft-thick soil liners showed low permeability ($2.0–3.1 \times 10^{-8}$ cm s^{-1}), which they maintained throughout the exposures. The apparent insensitivity of the native soil to various chemicals is probably related to its high ratio of nonclay to clay minerals in the fraction smaller than 2 μm. Another feature of this soil that may contribute to its insensitivity is the high salt content (it had been dredged from the channels in the Carquinez Straits in California and had dried on land). Except for the possible migration of copper, the other five metals tested (cadmium, chromium, lead, mercury and nickel) did not appear to migrate more than 2 cm (0.8 in) into the liner during 958 days of exposure to Oil Pond 104, which contained these trace metals.

3.1.2. *Asphalt concrete*

Combinations of the asphalt concrete and the oily wastes were eliminated in the screening tests. But in spite of the low permeability and good mechanical properties for the 6.4 cm (2.5 in) thick asphalt concrete, the liner was deficient in several exposures. Both specimens in contact with the strong acid (HNO_3–HF–HOAc) leaked. Some of the aggregate at the surface was dissolved, and the asphalt itself hardened severely during exposures that were relatively short (40 and 199 days). Leaks also developed in the specimens below the spent caustic and lead wastes. The lead waste contained sufficient oily constituents to cause the asphalt concrete to become almost a slush. Some seepage also occurred through the specimens. It was concluded that this type of lining material should not be used with wastes that contain oily compounds and that thorough testing of the aggregates is necessary. Also, a thickness of 6.4 cm (2.5 in) may be insufficient even for water and compatible dilute wastes.

3.1.3. *Bentonite and sand mixtures*

Polymer-treated bentonite and sand mixtures were tested in cells containing the lead, pesticide, slurry oil and Oil Pond 104 wastes. Tests with the acid and strong alkaline wastes had been eliminated in the screening test. The 13 cm (5 in) thick specimens exhibited low permeability ($< 10^{-8}$ cm s^{-1}), though the bentonite A specimens showed significantly lower permeability than the bentonite B specimens. This type of lining material is probably not satisfactory for oil wastes, since considerable "fingering" of the waste into the liner mass took place during the 980 days of exposure; none of the oils broke through the liner completely, however. Even though some flow of aqueous waste liquid through the liner occurred, the distribution of the metals in the liner at the various depths was uniform. The use of a soil cover on the liner to produce an overburden could probably reduce the fingering effect and reduce the flow.

3.1.4. *Soil cement*

The 10 cm (4 in) thick soil cement specimens showed resistance to spent caustic, the

Table 6
pH and electrical conductivity of water in outer bag and weight changes of filled pouches

Waste	Polymer	Liner number*	Pouch number	Elapsed time, days	pH	Electrical conductivity, μmho	Change in weight, %	Comments
Acidic—HFL	Chlorinated polyethylene	86 (22)	P45	1833	4.1	510	11.3	Pouch wrinkled, coated w/brown-green slime
	Elasticized polyolefin	36 (22)	P44	1833	3.2	60	0.4	—
	Polybutylene	98 (8)	P47	1833	2.9	155	0.7	—
	Polyethylene—low density	21 (10)	P43	1833	2.7	580	1.2	—
	Polyvinyl chloride	17 (20)	P48	1823	2.5	540	4.4	—
		19 (22)	P42	1833	2.6	280	3.9	Pouch wrinkled
		93 (11)	P46	1833	2.8	595	9.8	Pouch discolored, swollen
Alkaline—Slop water	Chlorinated polyethylene	86 (22)	P32	65†	7.9	270	2.7	Leak noted at 93 days; dismantled at 625 days
	Chlorosulfonated polyethylene	85 (33)	P31	2044	9.3	1800	36.5	Pouch wrinkled; blisters; odour in water
	Elasticized polyolefin	36 (22)	P30A	753†	12.4	10,800	213.6	Leaked at seam at 790 days; blisters noted
		36 (22)	P30B	1350	11.1	5460	227.8	Pouch swollen; has yellow crystals on it
	Polybutylene	98 (8)	P28	2044	9.4	1950	16.8	Pouch has small blisters
	Polyvinyl chloride	19 (22)	P29	872†	12.5	14,700	152.4	Pouch very stiff; seam failed at 930 days
		88 (20)	P33	65†	9.6	235	—	Leak noted at 93 days, dismantled at 625 days
Alkaline—Spent caustic	Chlorinated polyethylene	86 (22)	P26	2044	3.7	102	22.4	Pouch wrinkled; coated with brown-green slime
	Chlorosulfonated polyethylene	85 (33)	P25	2044	4.2	23	22.5	Pouch wrinkled
	Elasticized polyolefin	36 (22)	P24	2044	4.1	73	4.2	—
	Polybutylene	98 (8)	P22	2044	4.1	16	12.6	—
	Polyvinyl chloride	19 (22)	P23	2044	4.8	660	60.3	—
		88 (20)	P27	2044	3.3	94	54.9	Pouch seams wrinkled, swollen
Brine—5% NaCl	Chlorinated polyethylene	77 (30)	P6	—	—	—	—	—
		86 (22)	P77	316	3.6	86	4.0	Wrinkled at seams
	Chlorosulfonated polyethylene	6R (31)	P2	1151	7.4	585	10.2	Swollen
		55 (35)	P76	315	6.7	66	4.7	—
	Elasticized polyolefin	36 (22)	P4	1151	4.8	34	2.3	—
	Polybutylene	98 (8)	P78	316	5.1	27	0.7	Wrinkled
	Polyester	75 (8)	P7	928†	4.5	71	25.9	Leak noted at 955 days
	Polyethylene—low density	21 (10)	P75	315	4.4	31	0.9	—
	Polyvinyl chloride	11 (30)	P3	338†	—	22	0.4	Leak in seam at thin spot‡ noted at 791 days
		17 (20)	P73	310	3.1	371	6.5	—
		19 (22)	P74	315	6.4	16	1.8	—
		59 (33)	P5	1152	5.4	4500	2.1	—

Industrial—Basin F	Chlorinated polyethylene	86 (22)	P71	38†	4.3	38	1.0	Outer bag failed at 49 days
	Chlorosulfonated polyethylene	55 (35)	P70	1641	8.3	3600	10.8	Pouch wrinkled at edges
	Elasticized polyolefin	36 (22)	P69	1641	7.3	189	2.8	—
	Polybutylene	98 (8)	P72	1641	7.7	230	4.8	—
	Polyethylene—low density	21 (10)	P68	1641	6.0	330	10.9	—
	Polyvinyl chloride	17 (20)	P66	227†	4.7	33	7.5	Pouch smooth; leak in seam at 727 days
		19 (22)	P67	1641	8.0	600	29.7	Pouch slightly wrinkled
Lead waste	Elasticized polyolefin	36 (71)	P80	277†	5.2	11	−0.9	Pouch smooth; leak in seam at 726 days
	Polybutylene	98 (8)	P81	1638	7.9	315	−1.4	—
	Polyvinyl chloride	19 (22)	P79	1638	4.7	46	−1.2	—
Oily—Slurry oil	Elasticized polyolefin	36 (22)	P85	1638	3.2	59	0.0	Pouch wrinkled; oil on surface; stained
	Polybutylene	98 (8)	P86	1638	3.7	56	0.1	Pouch sticky; oil on surface; stained
	Polyvinyl chloride	19 (22)	P87	1638	4.0	42	0.6	Pouch wrinkled; oil on surface§
Oily—Oil Pond 104	Chlorinated polyethylene	86 (22)	P63	1485	4.5	190	1.81	Pouch flat
	Chlorosulfonated polyethylene	6R (31)	P56	1494	5.5	310	16.3	Pouch swollen, blistered
		55 (35)	P62	1485	5.5	320	12.9	Pouch flat, puckered
	Elasticized polyolefin	36 (22)	P61	1485	3.2	140	−1.3	Pouch flat, possible seam leak
	Polybutylene	98 (8)	P65	1485	3.4	130	−4.5	Oil on pouch outer surface
	Polyethylene—low density	21 (10)	P60	1494	3.2	130	−4.3	Oil on pouch outer surface
	Polyvinyl chloride	17 (20)	P57	1	—	—	—	Failed at 1 day
		17 (20)	P58	1485	2.8	330	−0.3	—
		19 (22)	P59	1485	3.8	49	−1.2	Pouch puckered and stiff
		93 (11)	P64	1†	5.9	6	0.0	Seam leaked at 9 days
Oily—Weed oil	Chlorinated polyethylene	86 (22)	P53	1654	4.0	420	10.3	—
	Elasticized polyolefin	36 (22)	P52	1654	3.3	52	0.3	—
	Polybutylene	98 (8)	P55	1654	4.4	39	−0.5	Brown sediment in pouch bottom
	Polyethylene—low density	21 (10)	P51	1654	3.4	46	0.9	Brown sediment in pouch bottom
	Polyvinyl chloride	17 (20)	P49	1640	2.5	448	0.3	Pouch has small blisters
		19 (22)	P50	1654	4.8	56	−0.2	Pouch has small blisters
		93 (11)	P54	62†	3.8	54	2.2	Seam open; pouch flat; noted at 78 days
Pesticide—Weed killer	Chlorinated polyethylene	36 (22)	P83	1638	3.2	67	0.3	—
	Elasticized polyolefin	98 (8)	P84	1638	3.3	46	0.1	—
	Polyvinyl chloride	17 (20)	P82	1638	3.4	42	−0.2	White rubbery sediment in pouch

*Matrecon liner serial number. Thickness, in mils (1 mil ≃ 0.025 mm) in parentheses.
†Leak detected in bag during next monitoring.
‡Thinness probably related to overheating during heat-sealing.
§This pouch was viewed under ultraviolet light and the oil fluoresced.

lead waste, the two oily wastes, and the pesticide waste. Soil cement was eliminated from exposure to the strong acid waste (HNO_2-HF-HOAc) in the screening test. No seepage occurred in any of the specimens. In the five that were recovered and tested, actual increases occurred in compressive strength. Metal concentrations were uniform throughout the depth of the liner. Note that these specimens were all small and not subject to the shrinkage or cracking that would be experienced in large installations.

3.1.5. *Sprayed-on asphalt*

When exposed to spent caustic, pesticide waste, and water, the sprayed-on asphalt performed well. A leak developed in one of the specimens in a cell containing brine. The sprayed-on asphalt had been eliminated from exposure to the oily and the acidic wastes during screening. In contact with the lead waste, it had softened considerably, and it absorbed water in all cases. Compatibility tests would thus be appropriate when considering sprayed-on asphalt for any impoundment linings. All oily or highly acidic wastes should be avoided.

3.1.6. *Polymeric membranes*

The polymeric membranes had a great variety of responses to the individual wastes, particularly to those with oily constituents. The effects varied from essentially no change during the exposures to complete failure. The screening tests eliminated several of the polymeric membranes from exposures to oily wastes in the primary cells. The varied responses of the membranes occurred not only among the different polymer types but also within a single type because of compound variations (e.g. plasticizer type and amount, cross-linking, and fabric reinforcement). The results demonstrate the importance of determining liner and waste compatibility during the selection and design process.

The results discussed here are for cross-linked polymers, thermoplastic polymers, semi-crystalline polymers and fabric-reinforced membranes with coatings based on either cross-linked or thermoplastic polymers.

The cross-linked polymers included two liners based on butyl rubber, two based on ethylene propylene rubbers, three based on neoprenes and one based on CPE. These membranes include both fabric-reinforced and unreinforced sheetings that were tested in both the primary and immersion tests. Cross-linking normally causes a polymer to swell less and resist changes in liquids more. This quality was observed in the liners based on CPE. All but one CPE liner experienced less swelling and fewer changes in properties with the cross-linked materials. In contrast, a thermoplastic ethylene propylene rubber (EPDM) sheeting had significantly lower swelling in the wastes than a cross-linked EPDM (the type usually used for liners). Note, however, that considerable differences exist in the EPDM rubbers and that some of them contain some crystallinity, which tends to reduce swelling. Seam failures occurred with butyl rubber, EPDM and neoprene, which were all prepared with cold-curing adhesives that tended to yield low adhesive strength. The failures all were in the adhesives.

The thermoplastic sheetings selected for this project included two sheetings based on CPE, four based on CSPE, eight based on PVC and one based on an EPDM. All of these materials tended to be sensitive to the type of waste, indicating the need for compatibility testing before selection as a waste liner. Polyvinyl chloride-based membranes varied considerably from sample to sample in their responses to a given waste. Test results ranged from major losses in weight to significant increases, and from near embrittlement to severe softening. This variation resulted from the effects

of compound differences such as plasticizers. The need for compatibility testing of the liner with the waste was quite apparent. The seams of the membranes that were based on thermoplastics retained their strengths during most of the exposures.

Semi-crystalline materials exposed in this project included one elasticized polyolefin (ELPO), one HDPE, two LDPEs, one polybutylene, one polyester elastomer (PEL), and one polypropylene. Of these semi-crystalline polymers, only the ELPO was a commercial product for liner use at the time this project was initiated. The PEL was an experimental material. The remainder were all commercially manufactured films, but not intended for liner use. They were tested because of their good chemical resistance and thus potential use as liners.

Among the polymeric materials studied in this project, the sheetings of semi-crystalline materials showed the least absorption of wastes and generally retained their physical properties best. Variations arose in that some of the crystalline materials, particularly the ELPO, swelled considerably in oily wastes. The ELPO had the lowest crystallinity of the semi-crystalline polymers examined.

The heat-sealed seams in the ELPO and PEL specimens essentially maintained their strength during the exposures. For both specimens, the lower values after exposure reflected softening of the liner itself.

The PEL exposed to the strong acid (HNO_3-HF-HOAc) failed completely and cracked. The ELPO absorbed considerable amounts of the alkaline slopwater and showed a major increase in permeability after about 1 year in the pouch test.

Since this project was initiated, new crystalline polymeric sheetings based on several of these polymers have been developed for use as liners and have become commercially available.

3.2. *Wastes*

Ten wastes and three media of known composition were used in the project. The ten wastes included two acidic, two alkaline, three oily, one lead, one pesticide, and one industrial brine waste. The three test media included dionized water, a 5% aqueous solution of sodium chloride and an aqueous solution of a trace organic, tributyl phosphate.

Overall, the deionized water had the least effect on the membrane liners, except for those based on elastometic polymers containing chlorine. In the sheetings based on neoprene, CPE and CSPE, the dionized water produced more swelling than the wastes containing salts yielded.

Oily wastes generally caused the greatest swelling and loss in properties of the polymeric and asphaltic lining materials. Oily wastes included slurry oil, Oil Pond 104 and weed oil. The lead waste, even though it was basically an aqueous waste, contained some low-boiling fractions, lead compounds and other gasoline additives and affected the polymeric and asphaltic materials in much the same way as the oily wastes.

Two types of nonoily wastes (i.e., acidic and alkaline) caused significant loss of plasticizer and stiffening of the PVC specimens.

The effects of immersing polymeric membranes in a dilute but saturated solution of an organic was investigated with a 0.1% solution of tributyl phosphate. The effects varied considerably among the 16 immersed membranes. After prolonged exposure the solution caused severe swelling and loss of physical properties of some materials. Semi-crystalline materials showed the fewest effects from the trace organic.

The nonhomogeneity of wastes and the sampling procedure posed problems in testing the compatibility of membranes and wastes. Some of the wastes became stratified so

that the waste at the bottom of a cell or tank had a considerably different composition from that at the top. Thus the specimens exposed horizontally at the bottom of a cell were not exposed to the same waste that suspended specimens were exposed to at the top. Such could also be the case with a pond liner when exposure at the bottom is compared with exposure near the top. Thus the possibility exists that a test specimen in a compatibility test may not be exposed to a representative waste from the impoundment or to a waste from a critical area in the pond. Two of the wastes were saturated with salts that crystallized out of the waste onto the liner, thus exposing the liners to wastes different from those in the initial waste solutions. Constant agitation of a nonhomogeneous waste during exposure testing may be a solution, but it may not result in a worst exposure condition. The effects of agitation should be studied to establish a compatibility test. More laboratory data are needed to develop background correlations with field exposure and actual service.

Within their respective groups, the more acidic and the more alkaline the wates were, the more aggressive they were to the lining materials. The spent caustic waste, which is essentially a saturated brine solution, behaved very much like the 5% brine and the briny industrial waste.

3.3. *Test methods*

The various test methods for characterizing changes in liners revealed significantly different responses among the liners upon exposure to each type of waste. The results of the different test methods appear to have some correlation with each other.

3.3.1. *Primary exposure tests*

The primary exposure cells and the test procedures simulated many conditions of waste exposure on the liners. During the one-sided exposures, the cells acted as permeameters with a head of 30 cm (1 ft) of waste liquid, and they yielded permeability data on the soil and bentonite compositions. The highly acidic wastes corroded the steel containers, presumably through pinholes in the epoxy coating. When the cells were dismantled, those that had contained acidic wastes were so badly damaged that they could not be reconditioned. The anti-rust paint used on the outsides of the cells generally was not satisfactory for the longer exposure periods, and the cells had to be repainted during service. For more recent projects, the cells have been epoxy-coated on both the outside and the inside during fabrication.

Test duration should be as long as possible. The 12- and 24-month exposures originally set in the contract were far too short for estimating service lives unless the latter were relatively short. Also, the number of exposure periods was inadequate for projecting some of the physical properties because of inherent errors arising from the nature of the tests and the problems in handling exposed specimens.

3.3.2. *Immersion test*

The immersion test exposed both sides of the membrane to waste and yielded somewhat faster responses than the one-sided exposures. The test also allowed the number of membranes that were exposed to be increased.

An immersion test can be adapted for use as a liner-waste compatibility test if at least four time exposures are used with at least 1 month between them. However, the immersion test should be investigated further to correlate it with actual experience.

3.3.3. *Roof rack exposure*

The roof rack exposure was an exploratory test to assess the effects of weather exposure

on a selected group of membrane liners. Exposure conditions in Oakland, California, are comparatively mild, but an exposure of 3 years 4 months showed many of the effects encountered in actual exposures of liners in service. Liner materials may be exposed to the weather at some point, but most are generally covered with soil when in actual service.

All of the membranes showed some changes in properties, but none actually aged to the point of serious deterioration. Most of the membranes lost in elongation at break and in weight and extractable content as a result of evaporation of plasticizers. All of the membranes shrank and tended to stiffen, and they generally gained in tensile strength. The CSPE membrane gained some weight. The PVC liners showed surface crazing and were the most severely weathered, as expected. In actual service, however, the PVC liners are generally soil-covered.

3.3.4. *Tub test*

The tub test demonstrates that different locations within an impoundment can have significantly different effects on the retention of properties by a liner. This test also shows that the most severe effects of exposure occur at the interface between the waste and the weather.

3.3.5. *Pouch test*

The pouch test was used here with thermoplastic and semi-crystalline membranes only. This test shows considerable promise for assessing the effects of a waste liquid in contact with a polymeric membrane liner. Results are shown in Table 6. Efforts should be undertaken to increase the applicability of this type of test to cross-linked sheeting and to stiff, thick sheetings. The test was run primarily with thinner sheetings that could be heat-sealed or solvent-seamed. The pouch test may have to be run for extended periods to observe long-term effects, and they may require interpretation until this test procedure has been used extensively.

3.3.6. *Seam strength tests*

Changes in the strength of seams incorporated into the primary exposure specimens were tested in both peel and shear modes. The effects of the exposure on seam integrity are best shown by the peel test, whereas the effects of the wastes on the liner are generally shown by the change in shear values. It is recommended that both tests be performed on the seams.

3.3.7. *Environmental stress cracking*

Possible stress cracking of HDPE in various waste liquids needs to be explored. This effect is not applicable to elastomeric and noncrystalline thermoplastic materials and was not studied in this project. However, HDPE has become an important material for the manufacture of liners, so accelerated environmental stress cracking tests should be developed to test the compatibility of semi-crystalline polymeric materials with wastes. The resistance of semi-crystalline materials to environmental stress cracking is presently tested by immersion in standard surfactant solutions.

4. Conclusions

The responses of the lining materials to the waste liquids and test media ranged from few or no effect to severe effects and failure. Oily wastes appeared to have the greatest

effects on polymeric membranes. Some organics, even at low concentrations, had severe effects after long exposures.

Because lining materials and wastes interact so variously because of their uncertain and complex compositions, compatibility testing of wastes and liners should be part of the liner selection process.

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